The Take into account of soil-structure interaction phenomena to study mining subsidence consequences on buildings

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Prise en compte des phénomènes d'interaction sol-structure pour l'étude des conséquences des affaissements miniers sur le bâti.

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ABSTRACT - The authors used a numerical finite element software for several modellings to study soil-structure interaction phenomena which occur during mining subsidences. We broke down the ground movements into several basic movements to highlight the impact and relative importance of each other (ground curvature and horizontal strain). We elaborate synthetic schemes of the ground and structure behaviour which improve the traditional apprehension of phenomena.

RESUME – Les auteurs ont utilisé un code de calcul aux éléments finis pour étudier les phénomènes d'interaction sol-structure qui ont lieu durant les affaissements miniers. Nous avons distingué les différents mouvements des terrains (déformation horizontale et courbure) afin de mettre en évidence leur impacte respective. Nous avons élaboré des schémas synthétiques, du comportement des terrains et des structures, qui permettent d'améliorer la conception traditionnelle des phénomènes en place.

1. Introduction

The underground mining of raw materials may be the cause of movements on the ground surface. Whether planned or accidental, such movements can cause considerable damage to structures located within the area of influence of underground mining work. This is borne out by the recent mining subsidences that took place at the end of the 1990s in the Lorraine iron-ore field. A better understanding of how ground surface movements can be imparted to the supporting structure and damage it, has now become necessary. Indeed, it is too often considered that damage depends only on ground strain with no account being taken of soil-structure interaction phenomena which may affect structural behaviour considerably.

We will first describe the ground movements caused by a mining cave-in. Then we will investigate the relative effect of each ground movement on a rigid structure, which behaviour is complex because of strong interaction between the ground and the structure.

2. Description of the phenomenon

Mining subsidences produce considerable horizontal and vertical movements on the surface of soils (figure 1). It is usual to consider, on the one hand, the vertical subsidence, the maximum value "Sm" of which is considered as a characteristic of the trough, and, on the other, the horizontal strain of the soil, its curvature and its slope which are the three movements loading structure and causing structural damage.

Methods for predicting structural damage generally use the definition of threshold values of strain and curvature from which such damage is expected. Some authors offer some behaviour schemes providing an overall view of the structure behaviour under the effect of each ground movement. A few examples of behaviour in a curvature area and in a strain area are shown in the figure 2 and figure 3.

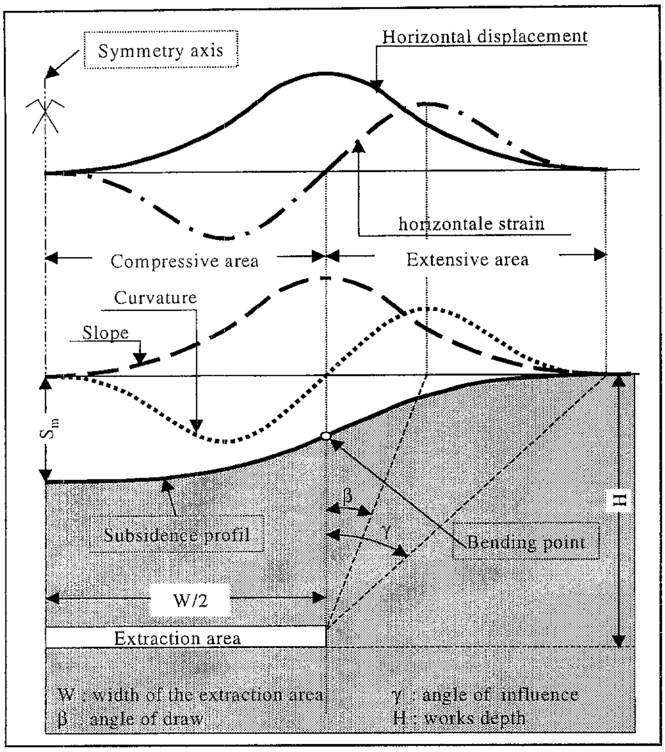

Figure 1 : Description of surface ground movements as a result of a mining subsidence.

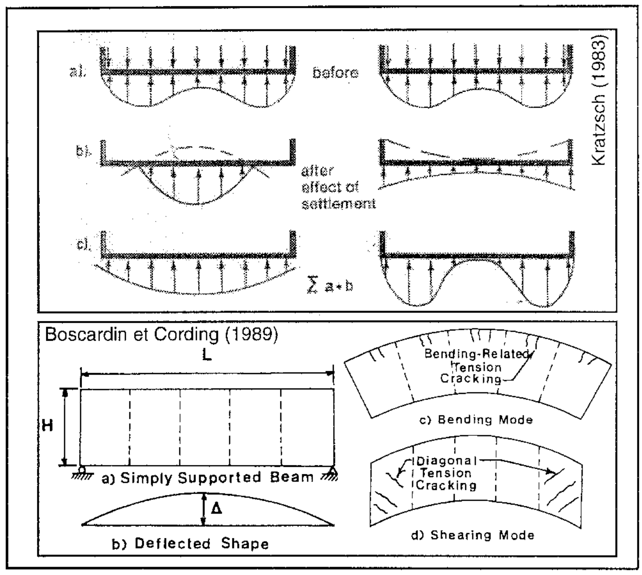

Figure 2: Behaviour of a structure in a curvature area

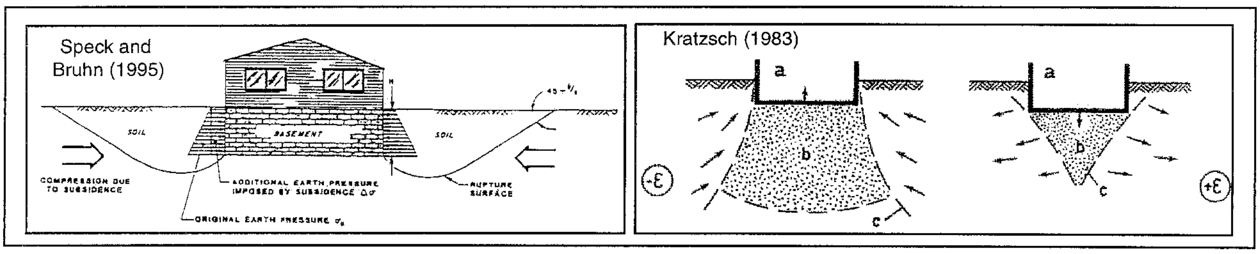

Figure 3: Behaviour of a structure in a strain area

The outcome of these few examples is that the fundamental question is whether soil movements are imparted integrally, partially or not at all. "Integrally" means that the structure is loaded by displacements, "not at all" or "partially" indicates the existence of complex soil-structure interaction phenomena.

3. Investigation of basic loading

The aim of this investigation is to highlight the overall behaviour of a solid-wall type structure, i.e. very rigid compared with the ground. For this purpose, we carried out a set of numerical modellings in order to investigate the behaviour of a structure with regard to each basic loading: horizontal strain and curvature. The effect of the slope was not investigated since the slope, as a rigid body movement of the structure, produces very few stresses in the structure.

We used the finite element software called CESAR-LCPC. Elements are six-node triangular, eight node quadrangular and six-node interface elements. The latter one make it possible to take into account a friction type behaviour with an interface separation possibility between the ground and the structure (zero cohesion and tensile strength, friction angle 20° and dilation angle 0°). In all the modellings, the ground behaviour was considered to be elastoplastic with a Mohr-Coulomb failure criteria (zero cohesion, friction angle 30° and dilation angle 10°). The structure was considered to be elastic. Thus, results which we are going to present here correspond to the structure and soil behaviours before structure damage. This choice is entirely legitimate given the very high mechanical strengths of the structure compared with those of the ground.

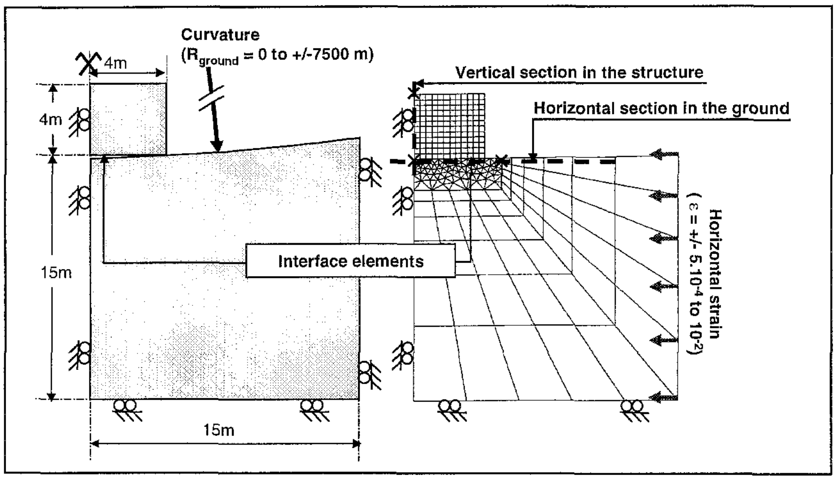

Figure 4 : Description of the models used to investigate the effect of the ground curvature and horizontal strain.

Two sets of models were produced, and are shown in figure 4. The first model is used to investigate the effect of a curvature of the ground. The second model is used to investigate the effect of a horizontal strain of the ground. The two models briefly represent a ground massive measuring 15 m by 15 m with a solid structure on its surface. The left border represents a symmetry axis. The calculations were carried out for plane strains. To model the effect of the ground curvature, we modelled the ground feature with a surface curvature (concave or convex curve) on which we modelled a perfectly horizontal structure. Between the structure and the ground, we placed interface elements which are initially detached except at the ends of the structure for the concave area and in the middle for the convex area. The ground was consolidated under its own weight, then we loaded it by the weight of the structure. The results were exploited by analysing stresses in the ground, in the structure and along privileged sections shown in figure 4. In addition, particular attention was paid to the localization of the failure points in the model. To model the effect of the horizontal strain of the ground (tensile or compression), the ground feature, whose surface is horizontal, was consolidated under its own weight and then loaded by the weight of the structure and finally deformed by imposing a uniform horizontal displacement on the right border of the model. Various curvatures (+/- 1000 m to +/- 7500m) and strains (+/- 0.5 10^{-3} to +/- 5 10^{-3}) were investigated as well as various Young modulus of the ground (30 to 100 MPa and Poisson's ratio 0.25) and of the structure (1500 to 15000 MPa and Poisson's ratio 0.2).

3.1. Curvature investigation

The effect of a curve of the ground on a structure is easy to understand. Figure 2 shows different schemes of the behaviour in a curvature area. In a concave area, we expect to observe a concentration of vertical stresses in the ground at the edges of the structure and in the convex area under the middle. We can compare these schemes with results of numerical modellings in figure 5 which show results in the whole model. Large changes can be observed of the plastified area, which differs from the area obtained in the reference investigation. The plastic points are concentrated perpendicularly to the areas on which the structure rests preferentially. They are thus deduced by the elevation of the vertical stresses.

The representation of the field of the main stresses highlights remarkably the redistribution of the stresses in the ground. The field observed in the structure revealed bending behaviour consistent with the ground curvature. However, the structure curvature is under no circumstances equal to the ground curvature. The structure stiffness is such that it retains a horizontal geometry. Tensile stresses appear in the lower fibre (0.1 MPa) in convex area and in the upper fibre in concave area.

The analysis of the vertical stresses in the ground under the structure shows that the disturbances are greater for a concave curvature than for a convex curvature. The vertical stresses in the ground, where the structure rests preferentially, increase by 60% in convex area and by about 100% in concave area. In addition, a structure is more likely to be found partially detached from the ground in the concave area than in the convex area. We can thus confirm the intuitive approach adopted by Kratzsch (1983), who suggested that the structure remains horizontal, compared to that of Boscardin and Cording (1989), who suggested that the curvature of the ground is transmitted to the structure. The study showed that the possible separation between the ground and the structure is not related to the bending flexibility of the structure but instead to the vertical flexibility of the ground.

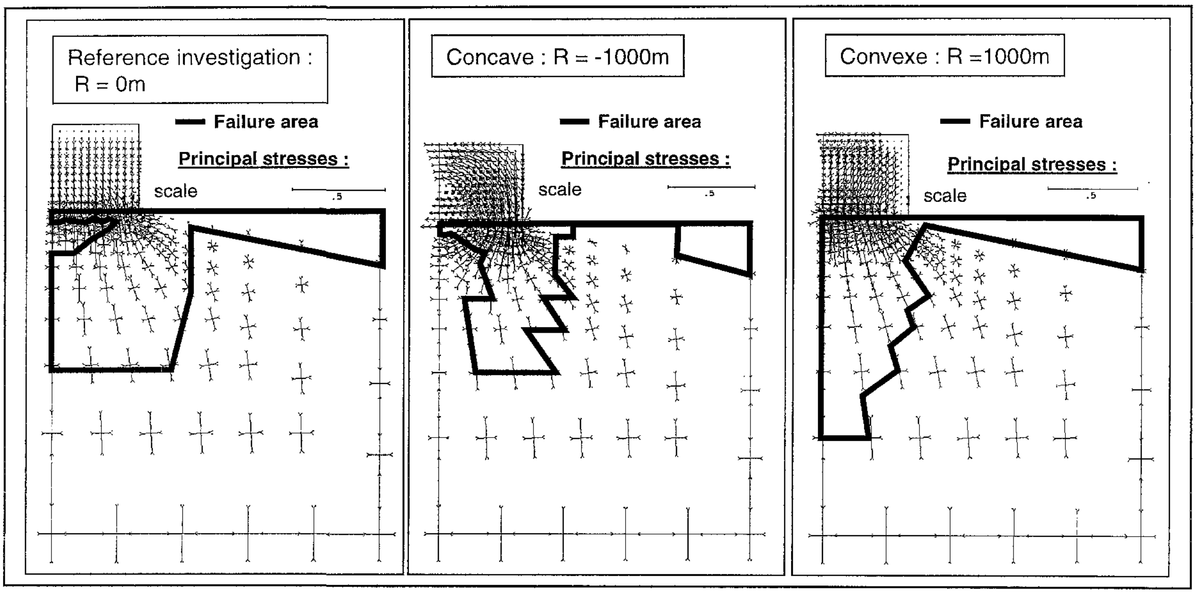

Figure 5: Stress fields and failure areas in a curvature area (+/- 1000m)

3.2. Investigation of strains

In the same way as for curvature, the effect of horizontal strain of the ground on a structure has often been grasped qualitatively (figure 3). The main idea adopted has been to assume that the horizontal strain of the ground only produces a uniform horizontal strain in the structure. The investigation presented here (figure 6) provides a visualization of the behaviour of a structure under such a movement.

The failure area in the model vary differently according to the strain direction. A generalised failure in the model can be observed in the tensile area, which can be readily understood given that the tensile strain tends to decrease horizontal minor stresses whereas vertical major stresses remain the same. In compression area, however, the presence of a confined area under the structure can be observed, similar to that obtained with the reference investigation (structure resting on a horizontal ground without strain) and which is similar to the cone of ground which remains integral under a vertically loaded foundation.

The stress field in the model shows that a compression strain generates a concentration of stresses in the ground under the middle of the structure as well as bending stresses in the structure. In a tensile area, however, the stresses seem to be relatively little modified in the ground or in the structure.

The variation in the vertical stresses under the structure provides a fuller explanation of the overall behaviour observed. The compression strain leads the structure to rest preferentially on its middle section. The increase in the stresses is then about 40%, i.e. an amplitude comparable with that observed for the curvature. In tensile area, however, a re-homogenization of the vertical stresses under the structure can be observed.

The horizontal stresses in the ground increase only slightly in tensile area. In compression area, however, a penetration of the horizontal stresses under the structure can be observed. No

increase of stresses is observed towards the edge of the structure. Indeed, the presence of the free surface of the ground, does not allow a significant increase in the horizontal stresses because the vertical stresses are very low. It is of interest to compare this result against one of the remedial actions proposed to minimise the effect of the strains: the digging of trenches around the periphery of the structure is often cited as a technical solution. But horizontal stresses observed on the ground surface are low because of the failure criteria adopted (Mohr-Coulomb). So, such a solution does not completely cancel the effect of the horizontal strain of the ground.
A shearing phenomenon appears naturally under the structure. Contrary to what is often assumed (Kratzsch, 1983), the effect of shear is not constant. In a compression area, the variation in the shear stresses is more complex. This phenomenon is associated with the distribution of the vertical stresses which vary significantly along the structure.

The structure is affected by horizontal strains of the ground much less than if such strains had been integrally transmitted. Indeed, a strain of +/- 5.10^{-3} would then have the effect of a horizontal stress of 25 MPa in the structure. Instead of such a value, the compression area causes a compression stress of –0.2 MPa in the lower fibre and a tensile stress of 0.1 MPa in the upper fibre. The structure is thus bent. To a less extent, the same phenomenon can be observed in a tensile area since the latter generates tensile stresses of 0.04 MPa in the lower fibre and –0.02 MPa in the upper fibre. Compression stresses distribution in the soil and the direction of shear stresses are both responsible for the bending observed.

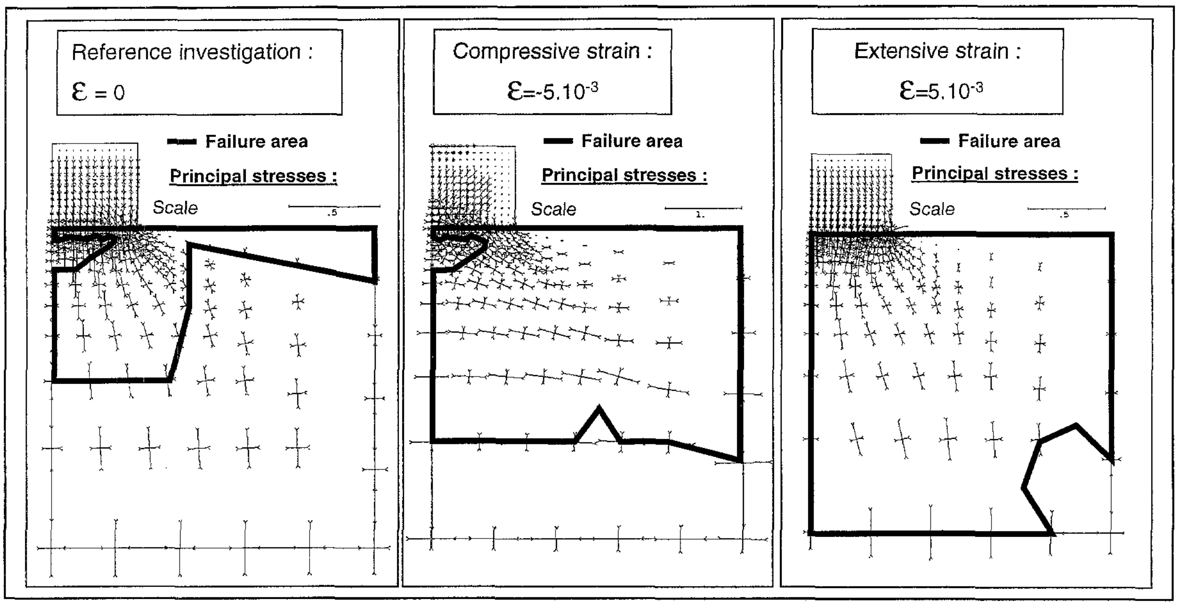

Figure 6: Stress fields and failure areas in a strain area (+/- 5.10^{-3})

3.3. Synthesis

Using the previous set of results obtained, added with those of parametrical study, it is possible to draw behaviour schemes of the structure in a curvature area or in a strain area. These models are shown in figure 7. These figures show the location of slippage lines and the distribution of vertical stresses in the ground and under the structure at various depths. These diagrams must be compared in figures 2 and 3. A number of elements are common. In particular, the slippage lines proposed by Speck and Bruhn (1995) or Kratzsch (1983) are fairly similar, which thus consolidates our results since, for the latter, the slippage lines had been observed experimentally on scale models in sand. The horizontal stresses observed along the middle section of the structure were also highlighted. The stresses are shown as a function of a parameter "a" for the single purpose of being able to make comparisons between them. These values correspond to the investigation presented in detail (E_{ground}=100 MPa, $E_{structure}$=5000 MPa).

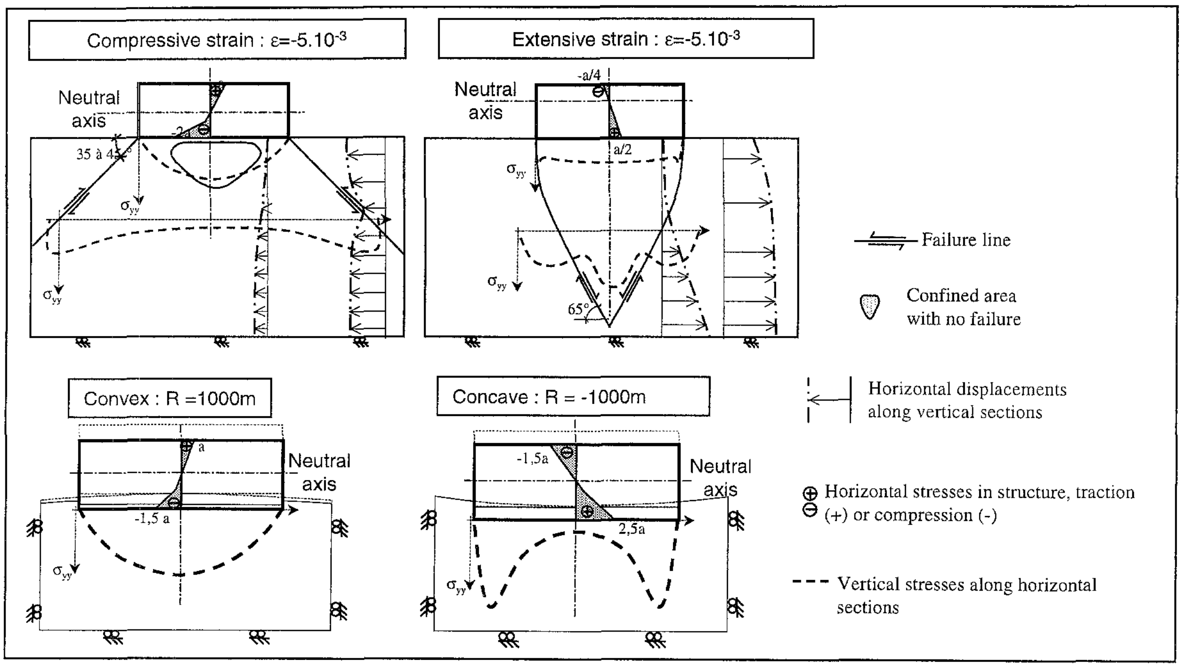

Figure 7: Behaviour of a structure with regard to horizontal ground strain and ground curvature.

4. Conclusions

The purpose of the investigation presented was to study the soil-structure interaction phenomena at work during a mining subsidence. Structures concerned are loaded, among other things, by a ground curvature and horizontal strain. Because of complex phenomena, we decided to dissociate the ground curvature from strain. The analysis provide a better identification of the various behaviours of grounds and structures under the effect of each ground movement. It remains for us to investigate the combination of these loadings. The main results of our investigation are outlined below:

- Soil-structure phenomena may be very important during subsidence so that buildings movements may be real lower and different from ground displacements.
- The investigation of the ground curvature is consistent with the intuitive behaviour schemes generally adopted.
- The strain investigation shows that the behaviour is more complex than assumed until now. In particular, strain causes a bending moment in the structure which is not negligible compared with the one induced in the curvature area. The effect of tensile strain is also to produce immediate failures in the ground which prevent stresses from being imparted to the structure.
- The numerical investigation made it possible to compare the effect of the various loadings with respect to each other and the effect of the ground mechanical properties.
- We propose overall behaviour schemes of a structure in a curvature area and in a strain area. The latter provides a better understanding of the phenomenon and a better assessment of the intrinsic effectiveness of the preventive measures to protect buildings.
- The overall behaviour schemes proposed in a tensile area would suggest that the structure stability cannot be guaranteed since the ground is no longer secured. Such instability cannot, however, be understood by means of the numerical software used.

5. References

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